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The design and experimental research of a mechanical testing apparatus for ultralow temperatures

Y.N. Huang[1, 2], W.T. Sun[1,*], C.J. Huang[1], R. Bao[1, 2], J.J. Dai[1, 2], L.H. Ma[3], W. Wang[4], J.J. Xin[4], L. Shi[1], L.F. Li[1,2], Y. Zhou[1,2]

[1] Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Research Institute of Interdisciplinary Science & School of Materials Science and Engineering, Dongguan University of Technology, Dongguan 523808, China
[4] Songshan Lake Materials Laboratory, Dongguan 523808, China
*E-mail: wentaosun@mail.ipc.ac.cn

Abstract. In future potential outer-space applications, the temperature of outer space associated with cosmic microwave background radiation is around 2-3 K. A mechanical testing apparatus was designed and manufactured for ultralow temperatures below 4.2 K by liquid helium evacuating refrigeration. The minimum temperature of this apparatus could reach ∼1.8 K. Using 304 stainless steel validates the equipment's test ability at ultralow temperatures below 4.2 K. The results showed that the tensile strength of 304 stainless steel decreased anomalously compared with 4.2 K.

1. Introduction

The mechanical properties tests of materials at low temperatures are crucial for the application of cryogenic structural materials. For example, in the field of nuclear fusion, structural materials are required to have good mechanical properties at 4.2K. However, in future potential outer-space applications, the temperature of outer space associated with cosmic microwave background radiation is around 2-3 K [1]. It has been reported that the yield strengths of some metals and alloys at ultralow temperatures (< 4.2 K) exhibit anomalous temperature dependence [2-3], which makes it necessary to evaluate the mechanical properties of structural materials at ultralow temperatures.

The electromechanical universal testing machine can be applied to various metal and non-metallic materials such as tensile, bending, shear, peeling, tearing, and other mechanical tests. Liquid helium evacuation refrigeration is one of the most commonly used methods for obtaining temperatures from 1 to 4 K [4-5]. In this paper, we designed and manufactured a cryostat for ultralow temperatures mechanical test suitable for electromechanical universal testing machine. A minimum temperature of ∼1.8 K can be obtained by pumping the liquid helium bath. Tensile tests with 304 stainless steel are performed at ultralow temperatures to verify the testing capability of the equipment.

2. Cryostat equipment

2.1 Design of cryostat
Fig. 1 shows the overall structure of the cryostat and electronic universal testing machine assembly schematic diagram. The cryostat is connected to the beam of the testing machine through connecting rod and flange. Above the flange is a liquid helium transfer pipe to transfer liquid to the inner specimen chamber, and there is a pumping tube to pump the vapor above the liquid helium. The cryostat is sealed with an O-ring between the cryostat and the flange plate. A liquid nitrogen chamber is provided inside the cryostat to cool the radiation shield inside the vacuum chamber. The radiation shield is covered with multilayer insulation to minimize radiative heat transfer. The vacuum chamber contains activated carbon to further reduce the vacuum level in the vacuum chamber. To reduce the heat leakage from the pull rod to the specimen, the pull rod is made of titanium alloy, which has higher mechanical strength and lower thermal conductivity. By reducing the diameter of the pull rod, the heat transfer from the pull rod can be further reduced. The diameter of the test chamber is 160 mm. Due to the large inner diameter of the test chamber, additional equipment, such as temperature sensors, strain measuring instruments, heaters, etc., can be easily installed in the specimen chamber.

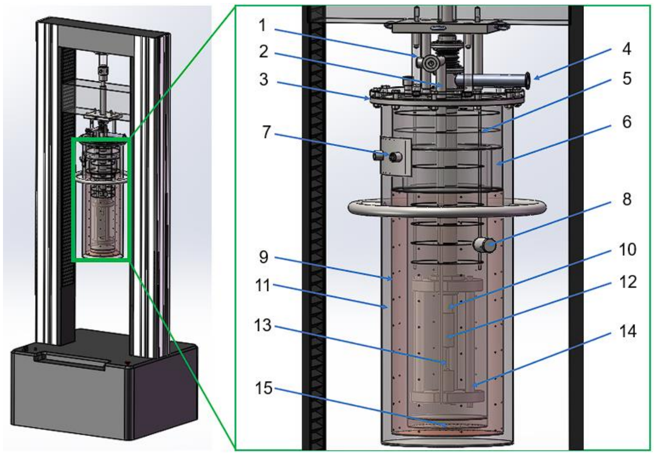

Figure 1. 3D-view of the cryostat and electronic universal testing machine assembly schematic diagram. 1. connecting rod; 2. Liquid helium transfer line; 3. flange plate, 4. pumping tube; 5. radiation shield; 6. liquid nitrogen chamber; 7. liquid nitrogen fill; 8. evacuation valve. 9. radiation shield; 10. pull rod; 11. outer vacuum chamber; 12. specimen grip; 13. specimen; 14. mechanical support; 15. activated coal.

2.2 Ultralow temperature tensile experimental process
The experiment was carried out by the relative motion between the pull rod and the cryostat. The specimen is fixed between specimen grips, the upper specimen grip is connected to the pull rod and the lower specimen grip is connected to the mechanical support. At the start of the tensile test, the beam of the electronic universal testing machine moves downwards so that the specimen is stretched by the specimen grips fixed to the tensile bar and the mechanical support. By changing the specimen grips, different sizes and shapes of specimen test trials can be realized.

To measure the temperature inside the specimen chamber, two silicon diode thermometers were arranged at the lower A and upper B positions of the mechanical support, as shown in Fig. 2. The silicon diode temperature was calibrated down to 1.4 K with a temperature measurement accuracy of 10 mK, which meet the accuracy requirements of the experimental tests. During the

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cooling process, liquid nitrogen was preferred to pre-cool the cryostat to reduce the consumption of liquid helium. At the same time, the liquid nitrogen tank is filled with liquid nitrogen to cool the radiation shield in the vacuum chamber. The liquid nitrogen in the cryostat is blown off before the liquid helium is transferred. To make full use of the specific heat of helium, transfer the liquid helium slowly at the beginning of the liquid helium infusion, a process that takes about 1 hour. When both thermometers reached 4.2 K, the chamber was filled with liquid helium for 5 min to meet the consumption of liquid helium during the pumping process. After the liquid helium filling was completed, an external pump was turned on to pump helium vapor from the top of the liquid helium bath to reduce the temperature. The pump is an oil-free mechanical pump with a maximum pumping speed of 10 L/s. During the cooling process, the tester was activated in a force-free mode so that it was moved automatically according to the thermal contraction of the mounted specimen.

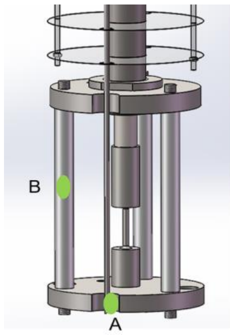

Figure 2. The locations of thermometers in the specimen chamber.

2.3 Ultralow temperature tensile test result

Fig. 3(a) shows part of the cooling curve of the cryostat. At the beginning of the liquid helium transfer, the cooling rate of the cryostat is slow due to the slow transfer of liquid helium and the larger specific heat capacity of the material. As the temperature approaches the liquid helium temperature, the rate of liquid helium transfer is gradually increased to allow the cryostat to collect liquid helium rapidly, and there is a clear temperature decrease at this point. When the upper thermometer reached 4.2 K, the liquid helium transfer was continued for 5 min and then stopped. When the mechanical pump is turned on, the vapor pressure above the liquid helium bath drops, and the temperature continues to decrease at a rate near 0.1 K/min.

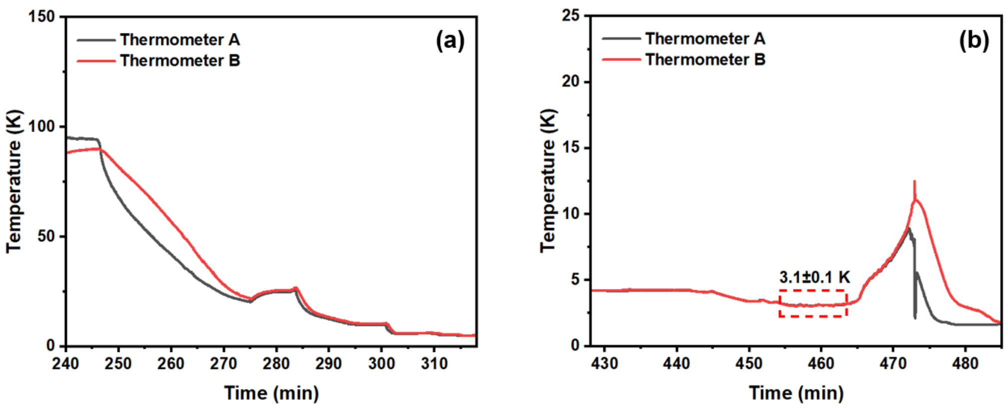

Figure 3. (a)The part cooling curve of cryostat; (b)The detailed temperature curve during the ultralow temperature tensile test.

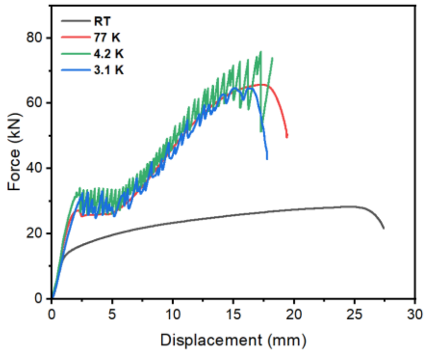

Figure 4. The force-displacement curves of 304SS at different temperatures.

Tensile tests were conducted using 304 stainless steel specimens at 3.1 K, 4.2 K, 77 K, and room temperature (RT). The detailed temperature curve during the 3.1 K test is shown in Fig 3(b). Before the ultralow temperature tensile test began, the temperature was first kept at 4.2 K for a period to reach initial thermal equilibrium with liquid helium. Then the mechanical pump was turned on. The temperature was controlled at 3.1 K and kept stable for 10 min to reach a new thermal equilibrium. The temperature control fluctuation not exceeding 0.1 K. Due to the low heat capacity of material in cryogenic temperatures, it is easier for the specimen to reach new thermal equilibrium. When the tensile test began, heat generated during the deformation of the specimen led to a temperature increase. After the specimen fractured, the temperature recovered to an ultralow temperature, which means the specimen was still immersed in liquid helium. The tensile test results of 304 stainless steel at different temperatures are summarized in Table 1. The tensile strength of 304 stainless steel decreased anomalously at 3.1 K compared with 4.2 K. The force-displacement curves are used in this experiment to represent the mechanical properties at different temperatures, and the force-displacement curves are shown in Fig. 4. It is obvious that the force-displacement curves at 4.2 K and 3.1 K exhibit typical serrated characteristics. However, the serrated characteristic also shows a difference in ultralow temperature. The number and the amplitudes of the “jump-like” deformation decrease at 3.1 K compared with 4.2 K. The mechanical properties of the material could be affected by the heat transfer conditions and the physical properties in ultralow temperature.

Table 1. Summary of tensile strength.

Temperature(K)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation(%)
RT	316	738	67
77	468	1717	41
4.2	577	1970	35
3.1	592	1680	37

Within the capacity of the pump we use, the lowest temperature the system could reach was ~1.8 K and kept stable as shown in Fig. 5. Due to the superfluid helium shift issue, the system is close to the temperature limit that liquid helium evacuation refrigeration can normally reach. Increasing the pump capacity might further reduce the minimum temperature of the system.

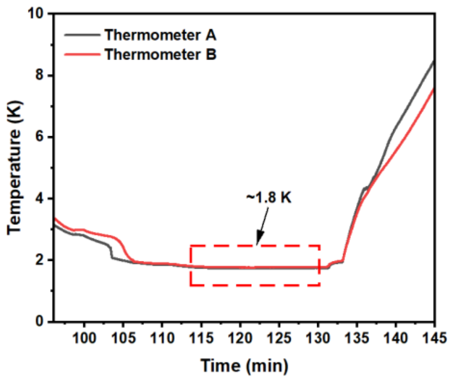

Figure 5. The minimum temperature of the apparatus.

3. Conclusion

An apparatus based on an electronic universal testing machine for mechanical tests was designed and assembled for ultralow temperature. The minimum temperature of this apparatus could reach ~1.8 K by evacuating the vapor above the liquid helium bath. An ultralow temperature tensile test was carried out at 3.1 K by using 304 stainless steel. Before the tensile test began, the ultralow temperature was kept stable for 10 min to reach thermal equilibrium. The results showed that the tensile strength of 304 stainless steel decreased anomalously at 3.1 K compared with 4.2 K.

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